*Wolfgang Schneider, DJ 8 ES*

# High-Precision Frequency standard for 10 MHz

**Since amateur radio began, frequency precision has been one of the most interesting (and simultaneously one of the most important!) subjects for radio enthusiasts. One point has been brought out time and again in various discussions with radio amateurs - frequencies must be measured with extraordinary precision, i.e. much more precisely than currents or component values. In spite of the technical options available today, most of the frequency counters available to us radio amateurs in the shack offer us display "accuracies" which, strictly speaking can not really be described as such. The same is true for the digital frequency displays in radio equipment. But what degree of accuracy will be useful while still being financially affordable?**

## 1.

## General

The accuracy of a frequency counter is determined simply and solely through the precision of the time base, if the error of ± 1 digit in the last display place is left out of consideration. The reciprocal value of the time base frequency deviation is equal to the error of measurement. If, as is usually the case, the counter has only a simple quartz oscillator, then its temperature dependence causes a considerable error. The same problem naturally also occurs with quartz oscillators in transverters, test transmitters, beacons, etc.. Nor is a PLL control circuit, which merely uses a simple quartz oscillator as a reference frequency, of any assistance here.

Normal quartzes are specified to have a temperature dependence of ± 30 ppm (parts per million) in the range from 10°C to 60°C. Better, and thus more expensive, quartzes can offer a level of accuracy of ± 10 ppm. Normally such temperature differences seldom occur within rooms, but are decidedly more frequent in portable radio equipment with a transverter, perhaps even up to 10 GHz.

To obtain a clear idea of the possible frequency deviation due to temperature, we should have a clear picture of the following ratios:

- ± 30 ppm corresponds to: ± 30 Hz at 1 MHz or else to a frequency error of:
- ± 300 Hz in a standard frequency counter with a measurement frequency of 10 MHz;

- ± 4,32 kHz at 144 MHz (2-m-Band)
- ± 38,9 kHz at 1296 MHz (23-cm-Band)
- ± 300 kHz at 10 GHz (3-cm-Band)

Against this background, making an sked with a frequency in a higher band (e.g. 10 GHz) is something which is really scarcely possible. Modern and narrow-band digital modes are just out of the question here.

To get a grip on this problem, there are generally two options:

- Stabilising the quartz oscillator temperature
- Re-setting the oscillator with the help of a frequency standard.

Combining both options is naturally better.

## 2.

## The temperature-stable oscillator

Special measures are taken in high-quality industrially manufactured frequency counters, and often in DIY equipment as well, to counteract temperature dependence.

For example, we can read in data sheets that the time base is generated with a TCXO. The abbreviation TCXO refers to a temperature-compensated or else temperature-controlled quartz oscillator. Whichever it is, the measures taken have the effect of restricting the quartz frequency to a maximum frequency error of ± 1 to ± 5 ppm in an acceptable temperature range. Better products, such as TCXO4 at 10 MHz from NARDA or a DIY oscillator for GHz applications, e.g. as per DF9LN, attain precision levels of ± 0.1 ppm.

The model HP 10544A quartz oscillator

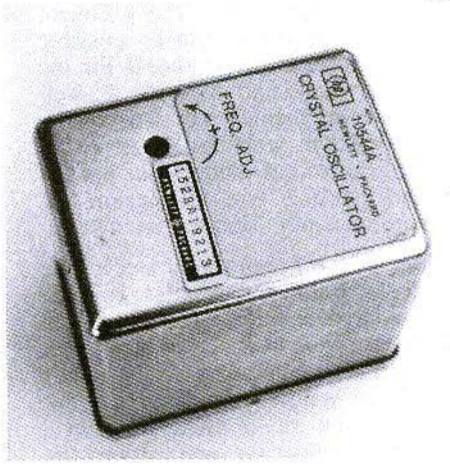



**Fig 1: HP 10544A Quatz Oscillator**

from Hewlett Packard is almost two powers of ten better, and this at a price which is still acceptable. In the temperature range between -55°C and + 70°C, the oscillator attains a stability of ± 0.015 ppm (1.5 x $10^{-8}$ ). In the range between 0°C and + 70°C, the value improves to 7 x $10^{-9}$.

The HP 10544A quartz oscillator is an

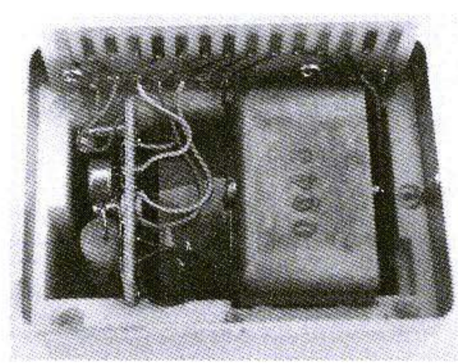


**Fig 2 Inside view of HP 10544A**

extremely stable reference source for 10 MHz with compact size. The excellent technical specification is made possible by a special production process for the quartz, in combination with a well thought out mechanical construction. A quartz oscillator, a buffer stage and a regulated heater are mounted in a well-insulated housing with dimensions of only approximately 7 cm x 5 cm x 6 cm.

Possible fields of application are, a time base for a frequency counter or as a reference frequency in test transmitters and test receivers or spectrum analysers. The oscillator can likewise be made available as a reference frequency for the production of a GHz frequency. Many other interesting applications are conceivable. All inputs and outputs are fed through a 15-pin connector block on the underside of the housing.

## 2.1

## The essential technical data of the HP 10544A:

- Output frequency: 10.000 MHz
- Output level: 1VRMS at 1 kΩ
- Power supply (DC): +11.0 V to +13.5 V / 15 mA (oscillator, buffer stage)

  +11.0 V to +13.5 V / 5 mA (heating control)

  +20 V to +30 V / 400 mA or 200 mA after 15 min./25°C (heating)

  -5 V to + 5 V (frequency tuning)
- Temperature stability: $1.5 \times 10^{-8}$ (-55 °C - +70°C), or. $7 \times 10^{-9}$ (0°C - +70°C)

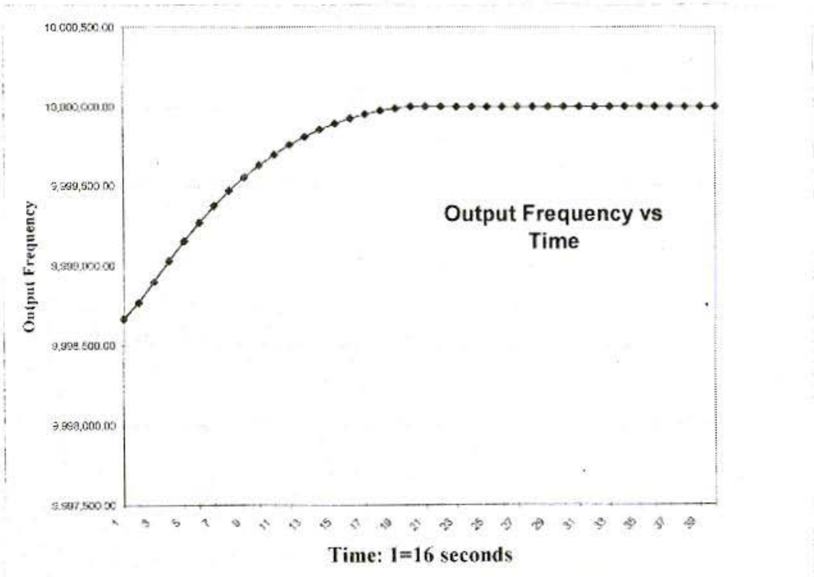



Fig. 2: Switching-on behaviour of HP 10544A

- Short-time stability: $1 \times 10^{-11}$ / 1s, or $2 \times 10^{-11}$ / 100 s
- Long-time stability: $< 5 \times 10^{-10}$ / day, or $< 1.5 \times 10^{-7}$ / year
- Side-band noise: -130 dB at 10 kHz
- Coarse tuning: ± 10 Hz (mechanical)
- Fine tuning: ± 0.5 Hz (electrical, -5 V to +5 V)

## 2.2. HP 10544A pin configuration (15-pin connector block)

**Pin Connection**

1 Output 10 MHz (1V / 1 kΩ)
2 GND
3 Oscillator (+12 V / 15 mA)
4 GND
5 GND
6 Tuning (-5 V..+5 V)
7 NC
8 Heating monitoring (+12 V 5mA)
9 GND
10 NC
11 Heating monitoring (Low = cold, High = warm)
12 NC
13 NC
14 Heating (+24 V / 200..400 mA)
15 GND

**Recommendations:**

- The oscillator (pin 3) can be powered from the 12 V source at Pin 8 through a 10 mH choke. Connect a 100µF / 25 V electrolytic capacitor to pin 3 for smoothing to earth.
- The operating voltages for the oscillator, the amplifier and, above all, the frequency tuning should be low-noise. V. Esper, DF 9 PL, has published an interesting circuit proposal for this in [3]

## 3.

## Buffer stage with analogue and digital outputs

The HP oscillator output is comparably high impedance at 1 kΩ. A buffer stage would provide a solution here. In the version proposed, 3 separated analogue 10-MHz outputs, each having 10 mW (-10 dBm) and additional digital outputs with TTL levels of 1 MHz, 5 MHz and, of course, 10 MHz are available.

In this connection it should be mentioned that any analogue outputs which are not in use should be terminated with 50 Ω, otherwise the mismatching will be reflected at the output back into the circuit.

The individual transistor stages are designed in such a way that the input impedance of 1 kΩ is obtained through a parallel circuit and is thus suitable for the HP oscillator. Fifth-order low-pass filters are also provided for the 3 analogue outputs. The harmonic content of the 10-MHz oscillator is thus considerably improved.

The buffer stage assembly (DJ 8 ES 046) is constructed using the SMD components to reduce space the double-sided epoxy printed circuit board measuring 60 x 100 mm.. The fully copper-coated rear side of the printed circuit board acts as an earthing surface. Short pieces of wire are used for feedthrough.

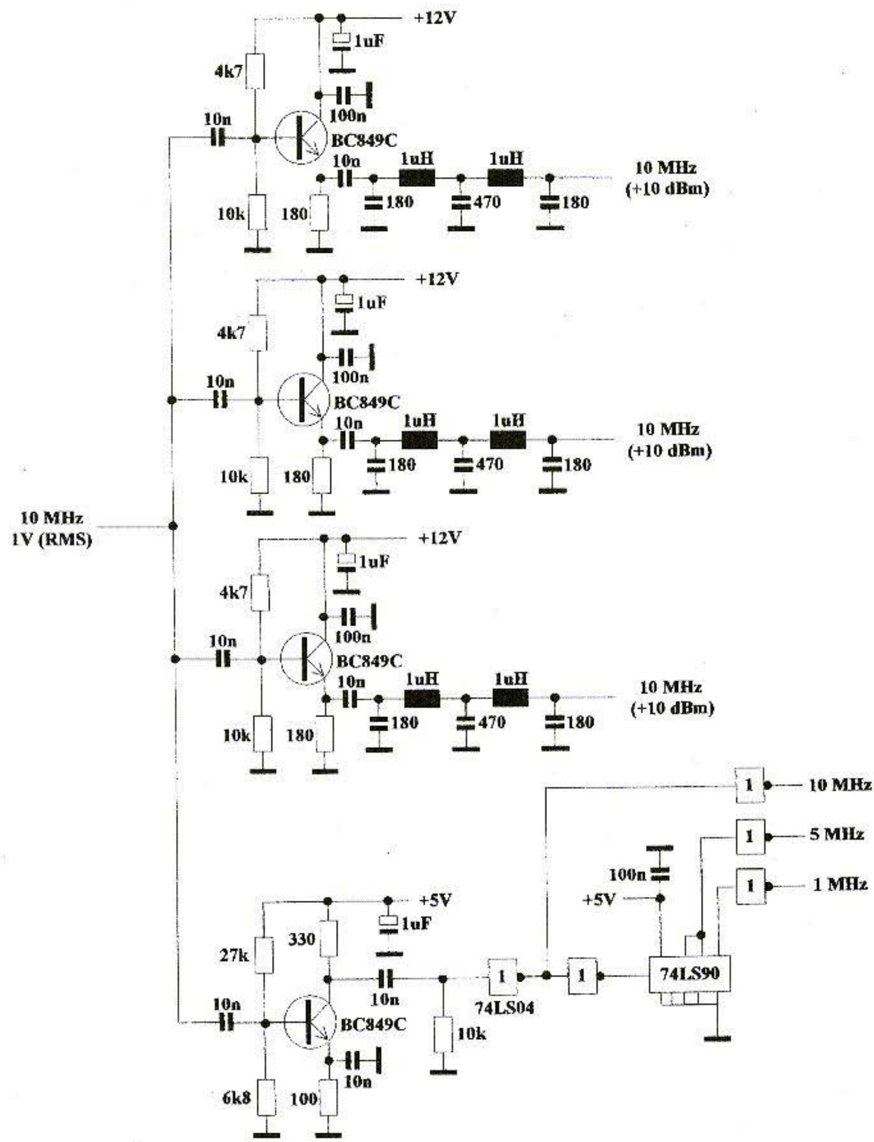



Fig 4: Circuit Diagram of Buffer Stage with Analogue and Digital Outputs

## 3.1.

## Buffer stage DJ 8 ES 046 parts list

4 x BC 849 C, Transistor
1 x 74 LS 04, TTL-IC
1 x 74 LS 90, TTL-IC
6 x 1µH, choke
4 x 1µF / 25 V, tantalum electrolytic capacitor
14 x terminal pin 1,3 mm
1 x DJ 8 ES 046, printed circuit board

Resistances:

1 x 100Ω , SMD
3 x 180Ω , SMD
1 x 330Ω , SMD
3 x 4.7 kΩ, SMD
1 x 6.8 kΩ, SMD
4 x 10 kΩ, SMD
1 x 27 k, SMD

Ceramic capacitors:

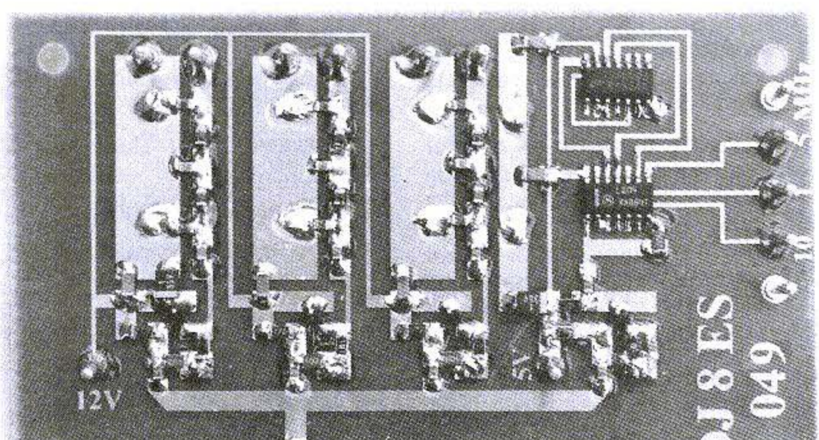
6 x 180 pF, SMD
3 x 470 pF, SMD
8 x 10 nF, SMD
5 x 100 nF, SMD

## 4.

## Outlook

High-precision oscillators of this type provide the user with a frequency standard which corresponds to, and perhaps even exceeds, the objective of attaining additional frequency precision set out at the beginning. This is irrespective of whether the oscillator is used as a reference source or as a time base in the frequency counter.

However, there is one fact which should in no way be overlooked: irrespective of the method selected or the quality of the temperature compensation, quártz ages -



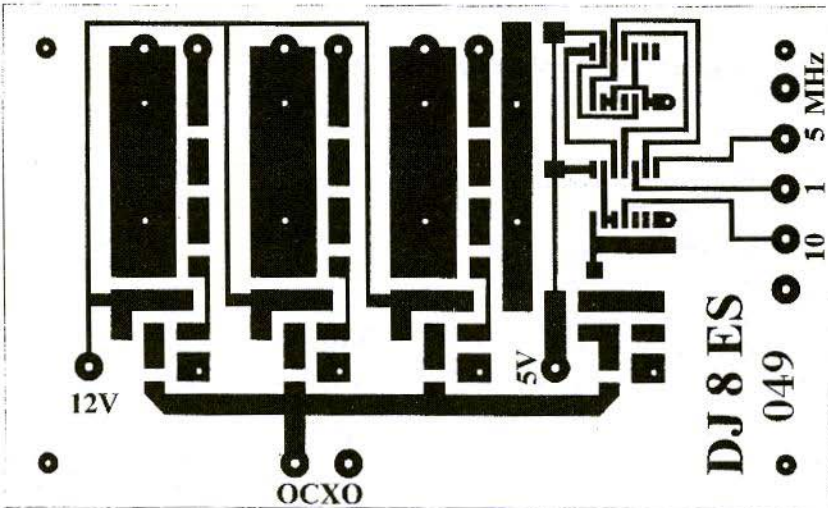



**Fig 6: Layout of PCDB DJ8ES 049 for Buffer Stage**

nor is this quartz ageing automatically compensated for!

For many high-quality quartzes, according to the manufacturers specifications, ageing can be up to 5 ppm per year, which corresponds to a value of at least 50 Hz at 10 MHz. The HP 10544A, has a value of $< 5 \times 10^{-10}$ / day (0.0005 ppm, 0.0005 Hz at 10 MHz), for operating round the clock, 7 days a week,...$< 1.5 \times 10^{-7}$ / year (0.15 ppm, 1.5 Hz at 10 MHz).

Anyone not able to carry out regular (annual?) calibration still has the option of having this done at one of the amateur radio congresses (e.g. VHF Congress in Weinheim). For it is not simple to carry out such a calibration by ear. An alternative to this is electronic re-adjustment using:

- the line frequency of a television transmitter
- longwave transmitters such as DCF77 or LORAN C, or
- with the help of the satellites of the Global Positioning System (GPS).

But this needs a separate article.

## 5.

## Literature references

[1] Frank Sichla, DL 7 VFS:

Precise frequency measurement but how?

Funkamateur 7/95, Theuberger Verlag Berlin

[2] Hewlett Packard (HP):

10544A 10 MHz Crystal Oscillator

Technical Data May 74

[3] Volker Esper, DF 9 PL: High-stability, low-noise power supply, VHF Reports 2/1992, Pages 81-93, VHF Communications 1/93, Pages 19-30

*Wolfgang Schneider, DJ8ES and Frank-Peter Richter, DL5HAT*

# High Precision Frequency Standard for 10 MHz

## Part II: Frequency Control Via GPS

**A high-stability frequency standard for 10 MHz can be created using only three system components. Short-term and long-term stability values can be obtained, by simple means, which far exceed the requirements for practical amateur radio operations.**

### 1. Introduction

The most commonly used method for precision time comparisons nowadays makes use of the satellites of the Global Positioning System (GPS). The GPS satellites (there are currently 26 of them) carry atomic clocks of the highest accuracy, the operation of which is carefully monitored by the ground stations. As in all relatively large institutes all over the world, the GPS is also used by the PTB for the international comparison of atomic clocks.

A stable quartz oscillator is regulated so well, with the aid of the GPS, that its maximum frequency deviation always remains better than $1 \times 10^{-11}$. This is a precision of 0.0001 Hz in 10 MHz! Or for the GHz amateur: 1 Hz in 100 GHz.

The frequency control via GPS shown in the block diagram (Fig. 1) can offer an accuracy of approximately $4 \times 10^{-10}$ or, in other words, 4 Hz in 10 GHz. This value results from the imprecision of the counting process built into the system. In frequency counters and this is nothing different the last bit should always be taken with a pinch of salt. Depending on the phase position of the gate time to the counting signal, an error occurs here of ±1 bit (phase error ±100 ns). For a gate time of 1s, that would be 1 Hz for the measuring frequency 10 MHz ($\pm 1 \times 10^{-7}$).

The first practical measurements were based on a gate time of 8 seconds, which corresponds to a resolution of 0.125 Hz. Together with the phase jitter of the GPS signal (1s cycle), there should have been uniform distribution and thus a levelling off of the reading over a relatively long period of time (max. 64 measurements). However, this turned out to be wishful thinking. From the measurement technology point of view, the situation with this gate time was that the oscillator frequency varied very slowly, or perhaps we should say it circled around the rated value of 10 MHz. The absolute frequency here was 10.0 MHz ±0.0305 Hz.

If the gate time is increased to 128

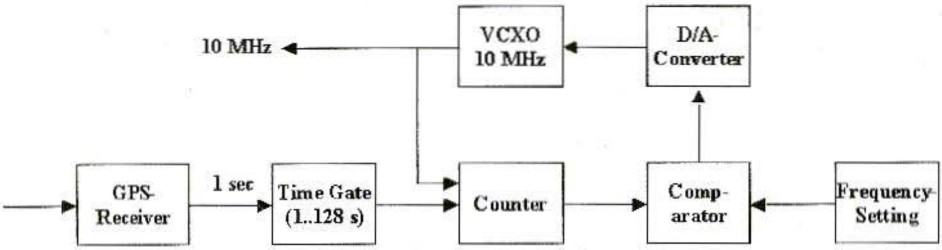



**Fig 1: Block Diagram of Frequency Control via GPS**

seconds, in theory the reading improves to at least ±0.0078125 Hz (±7.8125 mHz). However, the influence of the GPS phase jitter is now reduced. This results in an effective usable precision for the 10 MHz-Signals of approximately $4 \times 10^{-10}$ or, as already stated above, a frequency counter controlled on such a quartz time basis has a display accuracy of 4 Hz at 10 GHz.

## 2.

## The control assembly circuit

In principle, the control stage (Fig. 2) operates like a frequency counter with an additional numerical comparator. The oscillator frequency - 10 MHz of the HP oscillator HP10544A is counted out here. The gate time of the counter is generated from the 1pps signal of the GPS receiver with a 74LS393. For control operation, it amounts to 128 seconds and 8 seconds in the comparison mode for the OCXO.

The 74HC590 counter module is an 8-bit counter. It can be used, with a gate time of 8 seconds, to measure the input frequency 10 MHz ±16 Hz. The minimum resolution here is 0.125 Hz. In control operation (gate time 128 seconds), this is improved by a factor of 16. This results in the system-determined precision of $0.78 \times 10^{-9}$, based on the 10 MHz frequency oscillator.

The HP oscillator frequency can be finely adjusted using a tuning voltage of 5 V. This is done by the digital-analogue converter (AD 1851). It offers a resolution of 16 bits for a control voltage range of 3 V. This gives a setting range for the OCXO of approximately 0.5 Hz.

The AT89C52 micro-controller controls all the functions described above within the control assembly. The essential elements controlled which we should mention here are the meter module, the D/A converter and the status in the LC display.

## 3.

## Software description for controller

The software in the micro-controller AT89C52 performs two tasks. Firstly, it should enable a rough comparison operation to be carried out, and secondly it

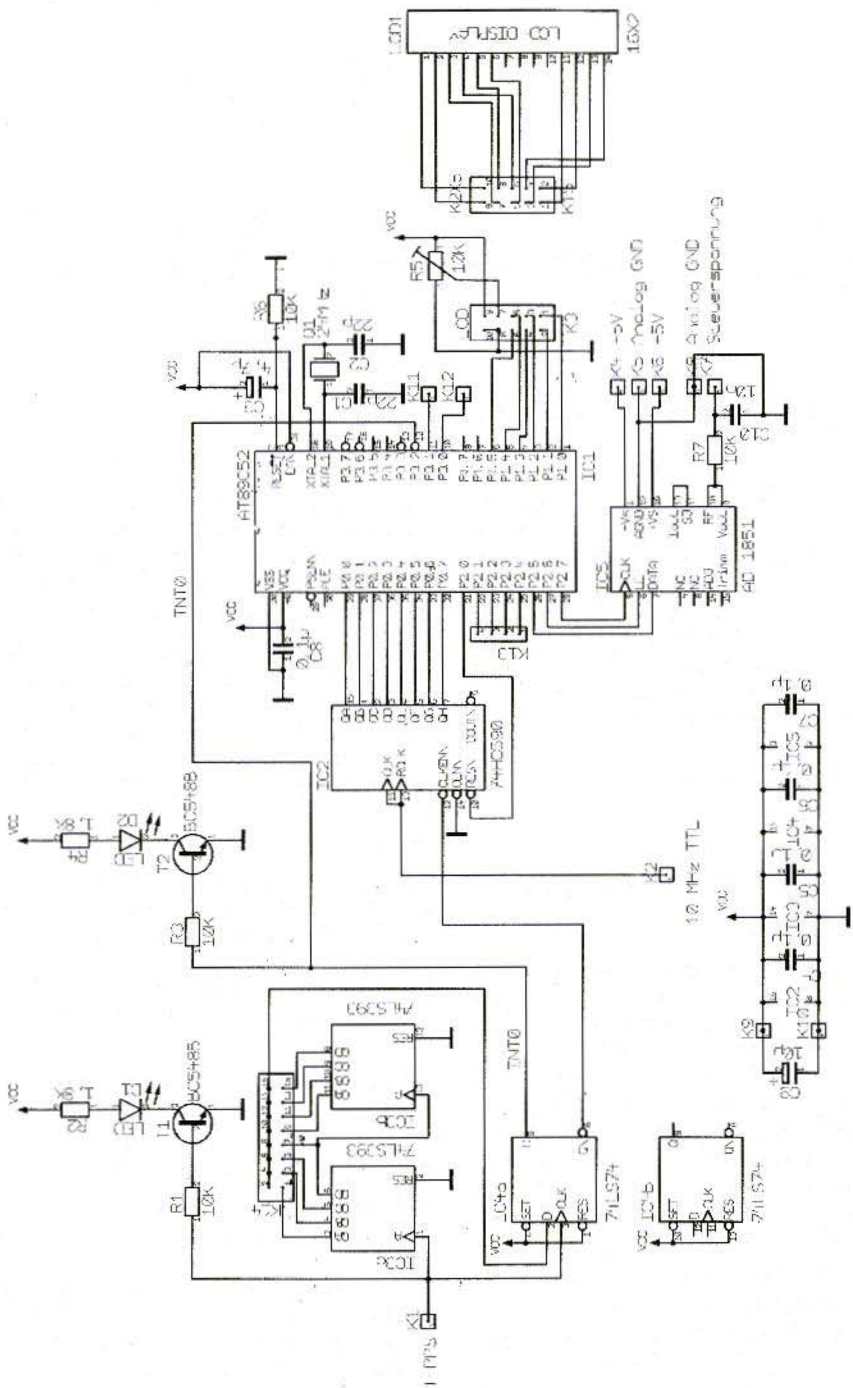



Fig 2: Circuit Diagram of Control Stage

will continuously carry out the final fine adjustment with the GPS signal.

If pin 4 of K13 is open, then when the voltage is applied to the control circuit board the LC display shows Warming Up. If the GPS second cycle is activated, the first value will be displayed after approximately 15 minutes. In order to eliminate any artificial jitter in the GPS second cycle, a mean value is formed and displayed from 64 readings from the 74HC590 meter.

A change in the oscillator frequency on the mechanical potentiometer will thus not display any effect for some time. So after a change on the potentiometer we must just wait for approximately 64 x 8 seconds until the next adjustment takes place. If a value of 0.250 Hz is attained, we can switch over to the basic control.

If the software in the controller is to recognise that the automatic control now has to be carried out, Pin 4 of K13 must be earthed.

The artificial jitter of the GPS signal and the very slight deviation following the rough comparison require there to be a relatively long gate time of 128 seconds. This is obtained by means of a bridge between pins 15 and 16 at K14.

Here too, the first message on the display is Warming Up. If the GPS second cycle is activated, the first value is displayed after approximately 15 minutes; though here it is not the deviation in Hz but the value which is written in the AD 1851digital-analogue converter. This value can reach a maximum of 32767, which means approximately 3V.

The software assesses the condition of the meter and, depending on the polarity sign, calculates the value for the AD 1851 digital-analogue converter. From the present condition of the meter and the mean of the last 64 meter results, the figure is determined which is to be added to or subtracted from the current digital-analogue converter value, which can be seen on the display.

According to pure theory, with the given gate time of 128 seconds and with a mean value formed over 64 readings, the time to reach the finally precision of

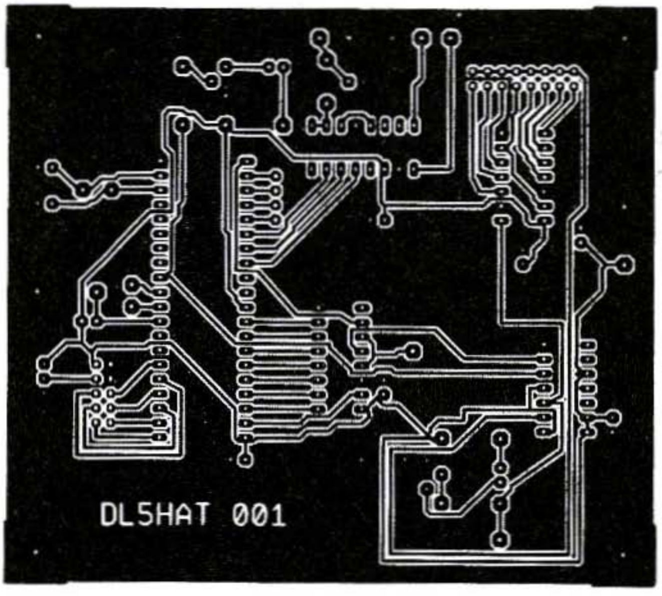



**Fig 3: PCB Layout for DL5HAT 001**

$4 \times 10^{-10}$ Hz (i.e. 4 Hz in 10 GHz!) is over after 4.5 hours. However, it has been demonstrated in practise that this value has already been reached after approximately two hours. It is important in this connection that the frequency deviation is not determined by the system alone but also depends on the number of GPS satellites which are currently being received, and the signals from which are available for evaluation.

## 4. Assembly instructions for control assembly

The frequency controller circuit is put together on a single sided epoxy circuit board, with dimensions of 100 mm x 100 mm (Fig. 3). Once the holes have been drilled in the circuit board, all the components can be fitted, in any order. The components drawing (Fig. 4) can be of assistance here.

The micro-controller (IC 1) should have a plug-in socket. Thus if the software is updated later, the processor can be easily replaced.

### 4.1. Control assembly parts list

| | |
|---|---|
| 1x µC | AT89C52 |
| 1x ADC | AD1851 |
| 1x TTL-IC | 74LS74 |
| 1x TTL-IC | 74LS393 |
| 1x TTL-IC | 74HC590 |
| 2x Transistor | BC848B |
| 2x LED | green, low current |
| 1x crystal | 24 MHz |
| 1x spindle pot | 10k |
| 1x socket strip | 10-pin |
| 1x plug strip | 10-pin |
| 1x stud strip | 14-pin |
| 1x jumper | |
| 1x PCB | DL5HAT 001 |

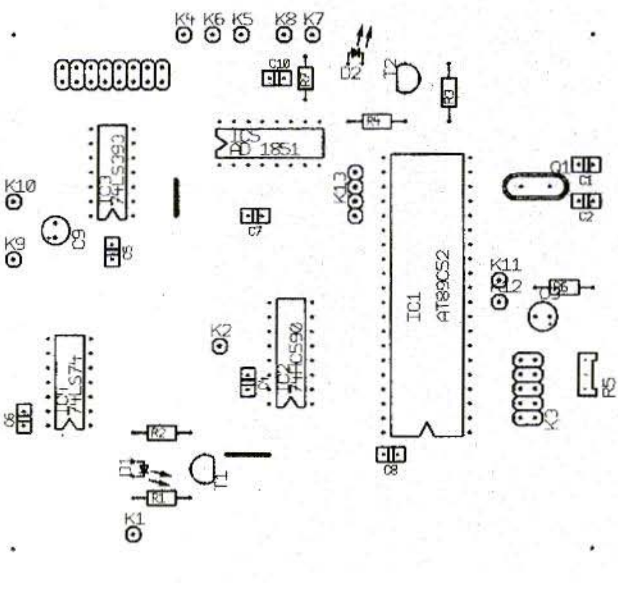



**Fig 4: Component Layout for PCB**

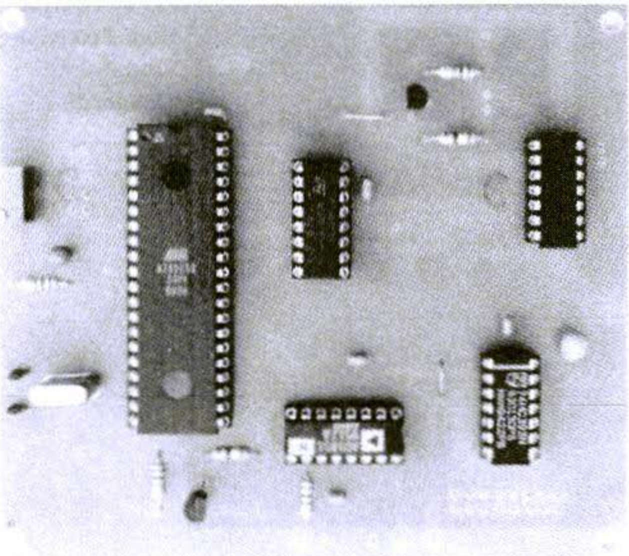


**Fig 5: Completed PCB**

**Resistors**

2x 1.8k

4x 10k

**Ceramic capacitors**

5x 0.1µF

2x 22pF

1x 10nF

**Tantalum Capacitors**

1x 4.7µF/25V

1x 10µF/25V

## 5. Inter-connecting all assemblies

The HP 10544A crystal frequency oscillator powers the DJ8ES 049 buffer stage. This makes available outputs for TTL levels (1. 5 and 10 MHz) and 3 separate 10 MHz sine signals on the output side. All connections are made to BNC sockets on the front plate of the apparatus.

The control assembly (DJ8ES 050) initially needs the synchronisation signal (1 pps) to generate the gate time for the frequency counter. This signal is generated in the specimen apparatus by means of a GPS receiver manufactured by GARMIN (GPS 25-LVS receiver board). The external aerial required is coupled through an SMA connection.

The frequency measurement input (10 MHz, TTL level) is connected in parallel to the corresponding BNC socket.

The control assembly output supplies the control voltage for the HP oscillator.

The tuning voltage, 5V, must be separately generated in the frequency controller power supply. The following concept would be ideal for the power supply in the frequency standard for10 MHz:

| | |
|---|---|
| +24V | HP oscillator |
| +5V | GPS receiver |
| +5V | control assembly |
| 5V | control voltage |


**Fig 6: Completed High Precision Frequency Standard**

The three keys on the front panel of the apparatus are intended to make it possible to show the status in the LC display. They are not taken into account in the present software version.

## 6. Operational experience

Long-term observations of the 10-MHz frequency standard over approximately 4 weeks confirmed the assumptions made in the introduction. Since it is not easy to measure the frequency directly in this way with the necessary precision, the analysis must be carried out through the tuning voltage of the OCXO. The oscillator frequency varies with a time constant of several hours around the value of $4 \times 10^{-10}$ Hz. The control software is being optimised again at the moment. The aim is to improve the deviation by a factor of 10.

To sum up, it must be admitted that a high-quality frequency standard for 10 Hz has been created using what is actually a decidedly simple method, and with minimal expenditure on hardware. This means that a reference frequency is now available in your own home at any time for frequency meters or frequency synchronisation, or for other applications. The accuracy of 4 Hz at 10 GHz (and eventually 0.4 Hz!) is certainly more than adequate for amateur applications.

## 7. Literature references

[1] Frank Sichla, DL7VFS: Precise frequency measurement but how? Funkamateur 7/95, Theuberger Verlag Berlin

[2] Wolfgang Schneider, DJ8ES: 10 MHz frequency standard using GPS: Congress Proceedings, Weinheim 1999

[3] Hewlett Packard (HP): 10544A 10 MHz crystal oscillator: Technical Data May 74